CHAPTER 8
THE DEATH OF STARS

8.1 Introduction

In this chapter we consider what happens to stars in the very last stages of their lives. We have already seen that stars are powered by thermonuclear reactions in their cores, and that over time, the fuel supplies for this nuclear burning become depleted. Eventually all stars reach a stage where energy can no longer be generated by nuclear reactions – either because the core temperatures never become high enough to trigger the fusion of heavier elements, or because the core has been completely converted into elements of the iron group.

■ What physical property of a star determines which of these outcomes occurs?

❏ Its initial mass. In stars with initial masses greater than about $11M_\odot$, core nuclear burning progresses to form iron group elements; in lower mass stars, core temperatures never reach the values required for nuclear burning to progress to this stage.

As you will see later, the formation of a core that comprises iron group elements gives rise to a spectacular instability in the star. This leads to the star being totally disrupted in a rapid and dramatic supernova explosion. In stars that do not form such a core, the end of stellar life is much more sedate. However these stars are subject to instabilities such as large-scale pulsations and intense outflows of stellar material.

Given the distinct differences between the ends of the lives of low- and high-mass stars, they are considered separately in the next two sections of this chapter. However, as you will see, there is a common theme to stellar death in both mass regimes: the enrichment of the interstellar medium with elements heavier than hydrogen and helium. Section 8.4 considers the effect of stellar processes on the composition of the gas and dust that constitute the material from which subsequent generations of stars are formed. The issue as to what remains of the core of the star – the stellar remnant – is an exciting topic in its own right and is the subject of Chapter 9.

8.2 The death of low-mass stars

In this section we look at the processes that mark the final stages in the life of stars with initial mass less than about $11M_\odot$. In Chapter 7 you saw how such stars evolve to form giants with helium burning cores. Following the exhaustion of helium in the core, the track on the H–R diagram moves back towards the region that was occupied when the star was a hydrogen-shell burning red giant (i.e. before core helium ignition) but now at a somewhat higher luminosity. This region is the asymptotic giant branch (stars at this stage of evolution are commonly referred to as AGB stars). As a star evolves up the asymptotic giant branch it starts to undergo thermal pulses due to shell

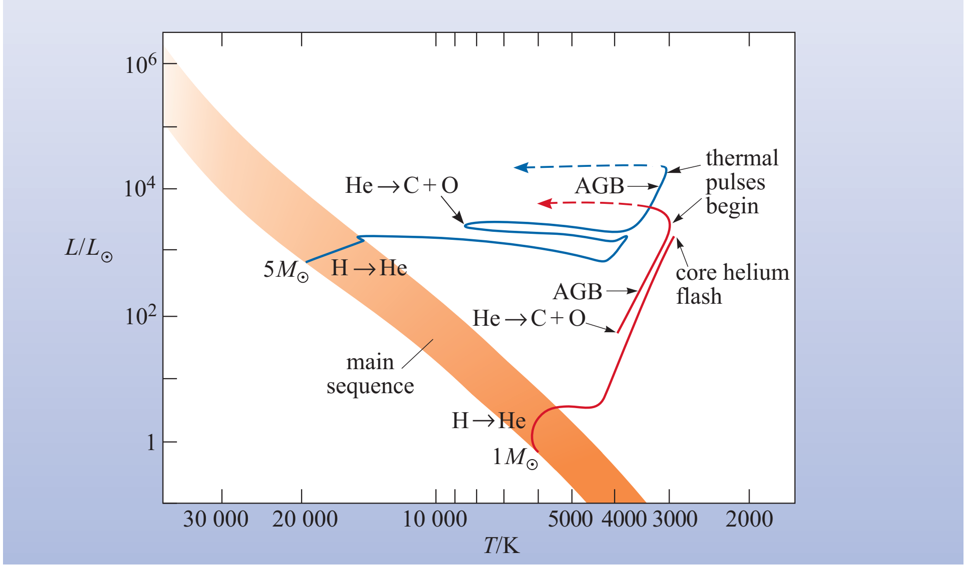


Figure 8.1 Evolutionary tracks on the Hertzsprung–Russell diagram for stars of masses of $1M_\odot$ (red line) and $5M_\odot$ (blue line) showing the progression from the main sequence to beyond the end of the AGB phase. The dashed lines at the end of the AGB phase indicate tracks that are not directly observable because of the presence of obscuring circumstellar material. Note that the main sequence is shown here as a thick band (rather than a line) to reflect the evolution that occurs during core hydrogen burning. (Adapted from Iben, 1991)

helium burning. These stages are indicated on an H–R diagram in Figure 8.1, which shows the typical evolutionary tracks of stars of masses of $1M_\odot$ and $5M_\odot$.

In this section we will look at processes that occur when a giant becomes a thermal pulsing AGB star and the immediate aftermath of this stage – the planetary nebula phase.

8.2.1 Pulsations and mass loss in evolved giants

Stars that have evolved to the stage at which they are undergoing shell helium flashes may exhibit global pulsations which are similar to those exhibited by Cepheid variables. These stars are called **Mira variables** after the prototype Mira (omicron Ceti) which varies in brightness by about 6 magnitudes with a period of about 331 days. Note that although Mira variables undergo global pulsations, their position on the H–R diagram is well away from the instability strip that is populated by Cepheids and RR Lyrae variables. In many Mira variables, the pulsation seems to be erratic and the relationship between period and luminosity is not as well defined as it is in the case of Cepheids. Furthermore the pulsation of Mira variables seems to cause considerable disturbance to the stellar envelope. Indeed, it is believed that the envelopes can become highly distorted from the spherical shape that the star had up until this time. Some indication of this is shown in Figure 8.2 which shows an image of Mira itself – its outline is clearly not circular. Although Mira is part of a binary system that may be partly responsible for distortion of its envelope, it is likely that such irregular shapes are common for stars at this stage of their evolution.

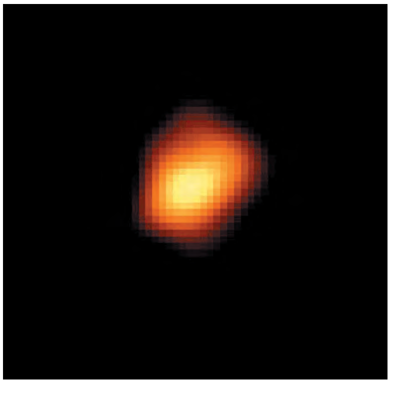
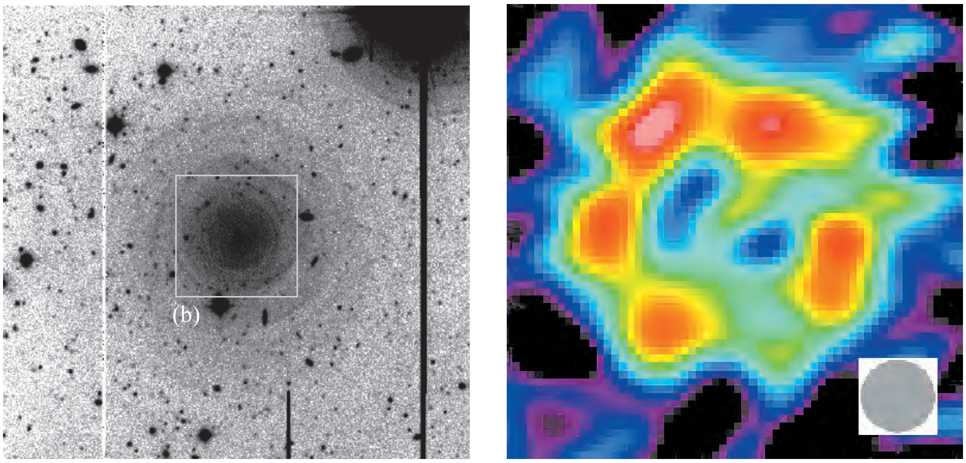


Figure 8.2 The star Mira as imaged at visible wavelengths using the Hubble Space Telescope. The envelope is clearly not spherical. In this image Mira is about 7 AU in extent.
(M. Karovska (Harvard-Smithsonian Center for Astrophysics)/NASA)

A second characteristic of thermally pulsing AGB stars (whether or not they exhibit Mira-like pulsations) is that they show very high rates of mass loss. As has been mentioned in Section 7.2.9, the mass loss rates during the very late stages of giant evolution may exceed $10^{-6} M_\odot\,\mathrm{yr}^{-1}$. Such stars are typically very strong sources of infrared emission, which arises from dust grains that condense in the out-flowing material. These grains are formed primarily from graphite or silicates. The presence of this dust results in the visible light from the star being very strongly absorbed or scattered. The out-flowing material is also a site for the formation of molecules such as hydrogen cyanide (HCN) and silicon carbide (SiC). In cases where a large amount of ejected material surrounds a highly evolved



(a) (b)

Figure 8.3 Maps of circumstellar material around the evolved star IRC+10216. (a) An image at visible wavelengths that primarily shows light that is scattered by circumstellar dust. This image shows a region around the star that is about 3×10^4 AU across. The dust cloud appears as a series of faint concentric shells which suggests that the star has undergone erratic episodes of mass loss. The square shows the area shown in (b). (b) A map made at microwave wavelengths that shows the emission from rotational transitions of a carbon-rich molecule called butadiynyl (C_4H). This map shows a region, again centred on the star, that is about 9000 AU across. The grey circle in the lower right-hand corner of the image shows the angular resolution of the millimetre-wave telescope that was used to generate this map. ((a) Mauron and Huggins, 2000; (b) Dayal and Bieging, 1993)

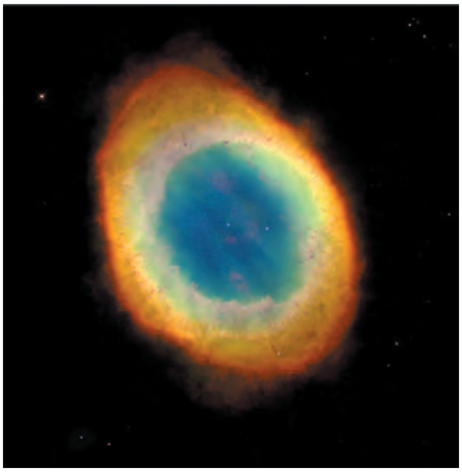
giant star, it may form a **circumstellar shell**. Figure 8.3 shows an example of an evolved red giant called IRC+10216 which is surrounded by a shell of material that contains copious amounts of dust and carbon-rich molecules.

Thus a key characteristic of the very late stages of the evolution of a giant is that it undergoes a very high rate of mass loss. This episode is the precursor to the next stage of stellar evolution – the appearance of a planetary nebula.

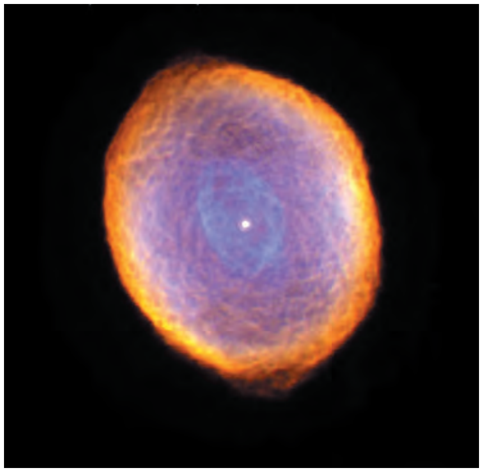
8.2.2 Planetary nebulae

Extended gaseous envelopes of the type shown in Figure 8.4 (overleaf), when observed in the 18th century, were given the name **planetary nebulae** because in small telescopes they appeared disc-shaped, like planets. However, the name, although universally accepted, is entirely inappropriate. These objects have nothing to do with planets! They are now known to be large, somewhat tenuous gas shells, also containing some dust, expanding with typical speeds of a few tens of kilometres per second. Their mass is typically between $0.1M_\odot$ and $0.2M_\odot$, and they are often associated with hot stars that are contracting while the envelopes themselves are expanding. Observations also seem to indicate that planetary nebulae are generally ‘disconnected’ from the star. They are also relatively common, with about 1500 having been detected in our Galaxy.

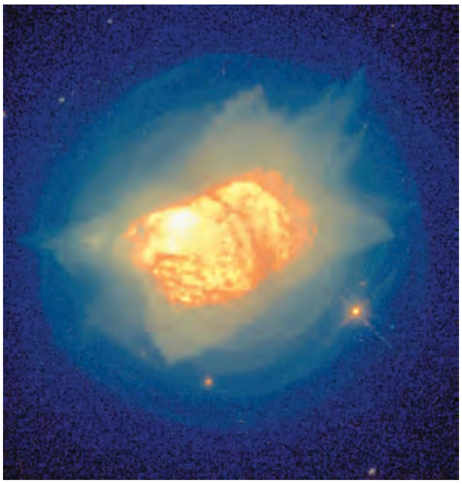
Although the first planetary nebulae to be discovered were those which appear circular, it is now recognized that many have a more complex structure, such as the example of IC 418 (Figure 8.4b). Many appear to be bipolar as shown in Figure 8.4e and 8.4f. It is a current matter of debate as to whether the bipolar nature is a result of the mass-losing star being in a binary system.



(a) M57



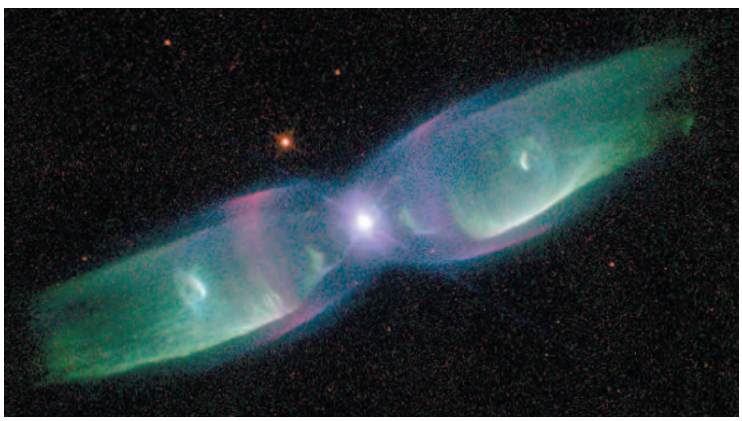
(b) IC 418



(c) NGC 7027

(d) Hen 1357

(e) Mz 3



(f) M2-9

Figure 8.4 Examples of planetary nebulae: These colour images are created by combining images made through filters that are responsive to particular spectral lines, e.g. in (a) M57 or the Ring Nebula, the colours represent emission as follows: green – ionized oxygen, red – ionized nitrogen, and blue – atomic helium.
(b) IC 418. This planetary nebula shows very intricate filamentary patterns.
(c) NGC 7027. The outer regions are ionized gas, the central cloud is rich in dust. The hot core is just about visible.
(d) Henize 1357 is believed to be a very young planetary nebula. It is thought that the clouds seen here were ejected in the last 20 years or so.
(e) Menzel 3 shows a clear bipolar structure, as does (f) M2–9.
((a), (b), (e) Hubble Heritage Team (AURA/STScI/NASA); (c) H. Bond (STScI/NASA); (d) M. Bobrowsky (Orbital Sciences Corp.)/NASA; (f) B. Balick (University of Washington)/NASA)

How do planetary nebulae fit into the picture of stellar evolution? All the evidence points to their being generated at the end of the giant phase or afterwards. The exact method of their expulsion is not completely clear. It is possible that they result from the pulsations of the outer layers of a star during a phase as a Mira-like variable, maybe being the result of pulsations that have grown very large. Alternatively, perhaps their release is triggered by the thermal pulses which arise because of shell helium burning. Another possibility is that, rather than a sudden expulsion of matter,

they may simply represent the continuing expansion and ultimate mass loss from a giant during its advanced stages of evolution. Whatever the generating mechanism, it seems that planetary nebulae dissipate into the interstellar medium about 20 000 years after ejection, leaving only the hot dense cores of their parent stars. The nature of these cores – stellar remnants – will be taken up in Chapter 9.

8.3 The death of high-mass stars

In Chapter 7, you saw how supergiant stars evolve rapidly to form an 'onion-skin' structure – concentric zones of nuclear burning around the core. On the final day of the life of such a star, the conditions in the core are such that silicon burning takes place and forms iron group elements (for brevity, this will be referred to as the 'iron core' in the discussion that follows). Since the iron group elements are the most energetically stable nuclei, the star runs out of fuel in a very abrupt fashion. It is at this point that we take up the account of the events leading to the dramatic end of the lives of high-mass stars.

8.3.1 Supernova explosions

When the reactions that produce iron diminish, the iron core must contract under gravity. The temperature and density increase still more, but now with no hope of further nuclear reactions that can release energy to provide a force to balance gravity. The collapse brings the central regions to a sufficiently high density that the electrons become degenerate. However, even though the electron degeneracy pressure is large, in these high-mass stars it is unable to halt the collapse; there is a maximum mass that can be supported by electron degeneracy pressure. Once the iron core has grown to more than about $1.4M_\odot$ it has exceeded this limit. Most stars whose main-sequence mass was greater than about $11M_\odot$ form, in the last stages of evolution, iron cores that exceed this limit.

So the electron degeneracy pressure will only temporarily delay the collapse, and then the core continues shrinking inexorably. The core temperature continues to rise, until at about 10^{10} K, the iron nuclei begin to photodisintegrate, producing α-particles, protons and neutrons. (These neutrons may be important for a process that will shortly be described: the r-process.) Unlike the earlier processes in which photodisintegration played a part in reactions that produced energy, the net effect now is one in which energy is absorbed. The core collapse gets faster and faster, reaching supersonic speeds. As the collapse continues, the density rises, as does the energy of the degenerate electrons. There comes a point where these electrons (e^-) have enough energy to make possible the reaction

$$e^- + p \rightarrow n + \nu_e$$

where n stands for neutron. This reaction removes electrons, so the electron degeneracy pressure drops and the core collapse proceeds in earnest. It stops, finally, when the core density becomes comparable with the density of the nucleus of an atom! The core temperature has risen to 10^{12} K and the core density has become approximately $3 \times 10^{17}\,\mathrm{kg\,m^{-3}}$!

At these densities a new form of degeneracy pressure, **neutron degeneracy pressure**, comes into play. This pressure, due to the neutrons, builds up quite quickly, causing the collapse of the inner part of the core to come to a sudden halt and rebound slightly. The overlying layers of the star are still falling inwards at speeds that may be as high as $70\,000\,\mathrm{km\,s^{-1}}$, so there must be a region where the gas flow undergoes a dramatic decrease in speed – a shock front (Section 5.3.1). This shock front moves radially out from the collapsed core and forms a shock wave.

QUESTION 8.1

The Earth has a mass of 6×10^{24} kg. What would be its radius if it had a density of 3×10^{17} kg m^{-3}, like the collapsed core of the star?

Exactly what happens next is still not completely clear, but it seems that some, or all, of the following things happen:

- The shock wave itself may blow apart the outer layers of the star, which consist mainly of lighter elements;
- The shock wave may heat the outer layers to a temperature of about 10^{10} K initiating explosive nuclear fusion reactions, which release enormous amounts of energy and throw off the outer layers of the star;
- Enormous numbers of neutrinos are produced and, although most of them escape without interacting with the outer layers of the star, sufficient may interact to lift off the material.

Whatever the detailed mechanisms, the net result is that the star suffers catastrophic self-destruction. The inner core of the star collapses to an enormous density, forming a body called a **neutron star** that is supported by neutron degeneracy pressure. The nature of neutron stars will be explored in more detail in Chapter 9; here we note that they have masses in the range of about $1.4M_\odot$ to $3M_\odot$ and a radius of only about 10 km or so. The collapse that forms a neutron star releases a huge amount of gravitational potential energy. Consequently, the outer layers of the star are blown off in a gigantic explosion. The star spent millions of years evolving to the point where it had a massive iron core, and then went through these last stages in seconds. The energy released by the core collapse is about 10^{46} J. At least 99% of this is carried away by neutrinos; the remainder goes into the kinetic energy of expansion (10^{44} J) and into the sudden brightening of the star (10^{42} J), with a little bit probably also going into the production of high-energy particles called cosmic rays. Typically, the star's luminosity brightens by a factor of 10^8, and it may for a while outshine the entire galaxy in which it is situated. An example of a supernova, supernova 2001CM, is shown in Figure 8.5. If the star lies within our Galaxy then it may be bright enough to be seen in daylight for a few weeks. It is called a supernova; nova means new

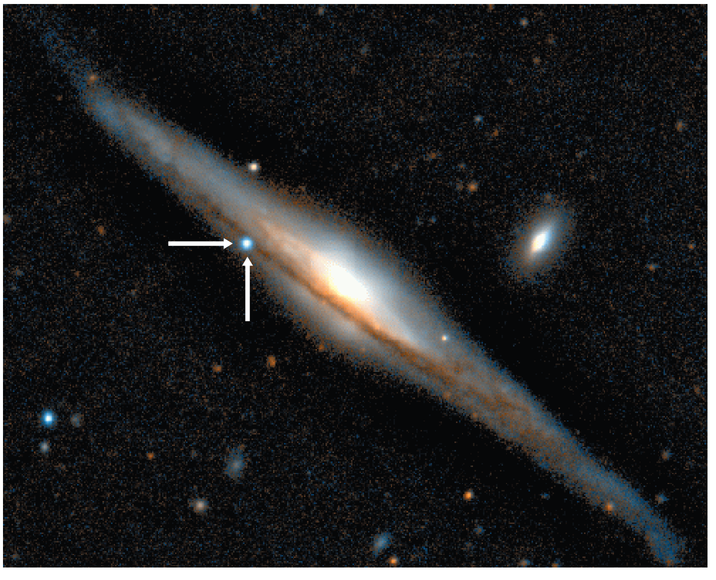


Figure 8.5 Supernova 2001CM in the galaxy NGC 5921. The supernova is the blue object indicated in the disc of the galaxy. Note that all of the other points of light in this image are foreground stars that lie within our Galaxy. This image was obtained about two months after maximum brightness. This supernova was classified as Type II on the basis of its spectrum. (H. Dahle (NORDITA))

(star) in Latin and a supernova is an extra-bright new star. This is a misnomer because it is the death throes of an *evolved* star that we are witnessing, but the name does remind us that what was previously an inconspicuous star suddenly brightens up and becomes noticeable.

Type I and Type II supernovae

Supernovae are classified into two broad groups depending on whether or not their spectra show hydrogen lines: Type I supernovae are those that do not show hydrogen lines, whereas Type II supernovae do. The supernova resulting from the explosion of a supergiant that has a significant amount of hydrogen in its envelope will contain hydrogen spectral lines and is thus likely to be of Type II.

For stars more massive than 30–40$M_\odot$, it is suspected that radiation pressure and the stellar wind may cause the star to shed its hydrogen envelope (see Section 7.3.5). If such a star subsequently undergoes a supernova explosion it will lack hydrogen lines in its spectrum and will be classed as Type I. In fact, there is a sub-division of the Type I class based on the presence of silicon absorption lines in the spectrum. Those with silicon lines are classed as Type Ia, whereas those that lack silicon lines are classed as Type Ib or Type Ic. The supernovae that result from supergiants that have lost their envelopes produce spectra of Type Ib and Ic.

The Type Ia supernovae are found in those areas of galaxies where there are old, slowly evolving stars, whereas Type II, Ib and Ic supernovae are associated with massive, young stars that have evolved rapidly to the supernova stage.

- ■ What does this suggest about the mass of most objects that become Type Ia supernovae?
- ❑ Because slowly evolving stars have low mass it suggests that most Type Ia supernovae are the explosions of low-mass stars.

At first sight this may seem a rather puzzling result, but the key to understanding this observation is that stellar evolution can be influenced dramatically if a star has a close binary companion. The influence of binary interaction on stellar evolution and the origin of Type Ia supernovae will be considered in more detail in Chapter 9.

8.3.2 Creation of heavy elements in supernova explosions

We have seen that fusion of light elements in stars can build nuclei as far as the iron group ($A \sim 56$), but cannot build further. However in Section 7.2.8 you saw that some elements can be built by another process, the s-process (s for slow), in which neutrons are added to nuclei. Some, but not all, of the isotopes beyond the iron group may be built this way.

To appreciate why the s-process cannot create certain nuclei, consider the following example. If we were to analyse a sample of the metal tin (symbol Sn) that had been obtained from tin-ore deposits on Earth, we would find that 4.6% of the mass of the sample would be in the form of the stable isotope ${}^{122}_{50}\mathrm{Sn}$. As we will see, it is not possible for this isotope to be produced by the s-process. The stable isotope of tin of lowest mass number (A) that is formed by the s-process is ${}^{116}_{50}\mathrm{Sn}$. If a nucleus of ${}^{116}_{50}\mathrm{Sn}$ were to capture a neutron, then a nucleus of the stable isotope ${}^{117}_{50}\mathrm{Sn}$ would be formed. To predict the effect of further slow neutron capture events, we need to know about the stability of isotopes to radioactive decay. Table 8.1 shows this information for isotopes of tin from mass number 116 to 122.

β^--decay is a type of radioactive decay in which a neutron is converted into a proton with the emission of an electron (e^-) and a particle called an electron antineutrino ($\overline{\nu}_e$).

Table 8.1 Stability data for some isotopes of tin (Sn). (Note that there are more isotopes of tin than are shown here.)

	Mass number *A*						
	116	117	118	119	120	121	122
type of radioactive decay	none	none	none	none	none	β^--decay	none
product of radioactive decay	–	–	–	–	–	$^{121}_{51}Sb$	–
half-life	stable	stable	stable	stable	stable	27 hours	stable

- Using the information in Table 8.1, which isotopes of tin can be formed by successively adding neutrons by the s-process to a nucleus of $^{117}_{50}Sn$? (Remember to assume that in the s-process, a neutron is captured by a nucleus about once every 10^4 years.)

- The isotopes of tin with mass numbers 118, 119, 120 and 121 will be formed by the s-process. However, on forming $^{121}_{50}Sn$ the nucleus will undergo β^--decay to $^{121}_{51}Sb$ (antimony) with a half-life of 27 hours.

Thus a nucleus of $^{121}_{50}Sn$ will almost certainly decay before another neutron can be captured. So, there is no route to forming the isotope $^{122}_{50}Sn$. Since this isotope is present on Earth, there must be another mechanism by which it can be synthesized.

- How could a nucleus of $^{122}_{50}Sn$ be formed in a process that involves the addition of neutrons to a nucleus of $^{121}_{50}Sn$?

- If neutrons could be supplied at such a rate that a nucleus of $^{121}_{50}Sn$ was more likely to capture a neutron than to undergo β^--decay, then this would result in the formation of a nucleus of $^{122}_{50}Sn$.

In creating some isotopes nature does just this. It is possible to rapidly add another neutron to an unstable nucleus before it has time to decay. This technique works where there is an abundant supply of neutrons, and involves a mechanism that allows the rapid absorption of neutrons by nuclei. Reactions embodying this mechanism are called **r-process reactions** (r for rapid), and are believed to occur in supernova explosions. The supply of neutrons comes from the break-up of the iron nuclei in the core, resulting in a flood of neutrons (10^{36} neutrons per square metre per second!). The r-process occurs for a few seconds only during the explosive expansion of the outer layers of the star, which have been heated to over 10^{10} K, and builds elements beyond iron. Moreover, the outer layers of the star, which are rich in hydrogen and helium, will very probably undergo a rapid sequence of nuclear fusion reactions, building elements predominantly of the iron group. Heavier elements ($A > 56$) are created in the explosion by the r-process, and certain of these, such as gold and plutonium, are created predominantly by this means.

However, it is important to appreciate that elements with mass number up to $A = 209$ ($^{209}_{83}Bi$) can also be created by the s-process in lower mass giant stars, although as we saw in the example of tin, there are often particular isotopes of an element that cannot be formed in this way. Terrestrial samples of a given element are typically mixtures of nuclei that were formed in s- and r-process reactions long before the formation of the Solar System. So, for example, the origin of the nuclei in a terrestrial sample of barium (Ba) is estimated to be 89% from the s-process and 11% from the r-process. In contrast, most nuclei in a sample of europium (Eu),

were formed mainly by the r-process (97%) with only a small contribution (3%) from the s-process.

A Type II supernova explosion provides not only an environment in which heavier elements ($A > 56$) are created by the r-process, but also the mechanism for distributing them through a large volume of space. Elements, such as silicon, sulfur and magnesium which were formed earlier by nuclear fusion in the core of the star are also ejected as the explosion shatters most of the star. Supernova explosions are the most important way in which the chemical composition of the interstellar medium is enriched with elements heavier than neon.

8.3.3 The supernova light curve

Type II supernovae have hydrogen emission lines in their spectra; Doppler shifts (Box 3.1) of these lines observed in recently exploded supernovae show material expanding outwards at speeds of up to $10\,000\,\mathrm{km\,s^{-1}}$. For about a month the visible surface of the star expands steadily at several thousand kilometres per second; as the surface area increases so the amount of light radiated increases. Then the brightness begins to fade as shown in the light curve in Figure 8.6. When the visible surface has expanded to a radius of about 2×10^{10} km it becomes transparent, and the amount of light produced drops markedly.

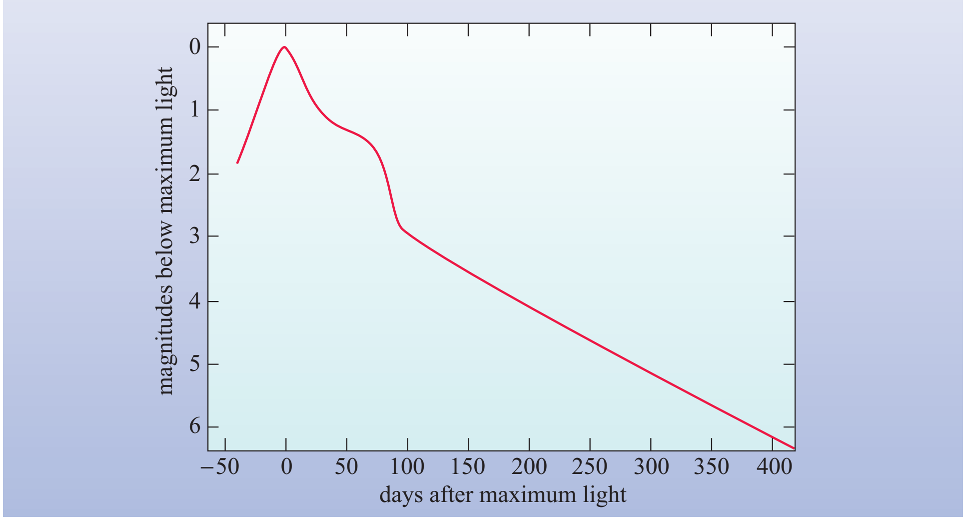


Figure 8.6 The light curve of a typical Type II supernova.

QUESTION 8.2

How does this radius of 2×10^{10} km compare with the radius of a supergiant, the radius of the Solar System, and the distance to the nearest star?

We discussed earlier how, when building heavier elements step by step from lighter ones, unstable (that is, radioactive) nuclei can bring the building process to a halt. Radioactive nuclei have other effects too. In particular, the type of radioactive decay in which a γ-ray is emitted can be important for the brightness of a new supernova. It has been suggested that such γ-rays are the energy source governing the brightness of a supernova for the period starting six or eight weeks after the explosion. The most likely decay sequence is ${}^{56}_{28}\mathrm{Ni}$ rapidly decaying to ${}^{56}_{27}\mathrm{Co}$, which in turn decays more slowly to ${}^{56}_{26}\mathrm{Fe}$ with the emission of γ-rays. We shall see later, when we discuss supernova 1987A, that this suggestion has been confirmed.

Note the usage of the words visible and optical. Optical wavelengths are the visible wavelengths plus the near infrared and the near ultraviolet wavelengths. This corresponds to a range of wavelengths from 300 to 900 nm that can be observed through the Earth's atmosphere.

Note that the brightness or luminosity plotted, in light curves such as Figure 8.6, is that measured in the optical part of the spectrum. Why should it be the optical data that are used? Supernovae are rare occurrences and our understanding of them has been achieved by putting together all available data. Because optical telescopes have been and are more numerous than, for example, neutrino detectors or far-ultraviolet telescopes, most of the available data are from the optical wavelength band. Also, although most energy is lost through neutrino emission, neutrinos are difficult to detect. Thus for studying the evolution of the supernova over the subsequent weeks and months the optical radiation emitted is a more useful diagnostic.

Often we miss the initial rise in optical brightness as the photosphere of the star explodes, noticing the supernova only when it is close to maximum brightness, some weeks after the explosion. The shape of the light curve after maximum brightness depends on both the radius and the temperature of the visible surface (remember Equation 3.9). For the first 25 days or so after maximum brightness the visible surface is still expanding but, nevertheless, the effects of falling temperature dominate and the luminosity drops. The majority of Type II supernovae have a curious shoulder, or plateau, in their light curves between days 25 and 75 after the maximum. The outer layers of the star are thinning so we are seeing further into it; but meanwhile the star is expanding in a way that just balances our ability to see deeper into it. Like walking down the up-escalator, the net result is that the surface we see does not appear to move much – the radius is roughly constant. So too is the temperature, and hence the brightness does not change much, giving the shoulder. After about day 75, we start to see further into the star, so while the outer layers of the supernova are actually expanding outwards, the *visible* surface appears to retreat rapidly. Although the temperature remains roughly constant, the shrinking radius causes the luminosity to fall abruptly. From 100 days after the maximum, radioactive heating by γ-rays controls the brightness, and the shape of the light curve is governed by the half-life of the radioactive decay.

8.3.4 How common are supernova explosions?

The last supernova seen in our Galaxy was in AD 1604 – before the telescope was invented! And before that, we know of ones in AD 1572, AD 1054 and AD 1006. So, at first glance, a rate of roughly 4 in 1000 years would seem appropriate for our Galaxy. However, supernovae at maximum brightness can be as bright as a whole galaxy, so we can find them also in other galaxies. For these, the rate seems to be one every 25 to 50 years per galaxy – a very different rate.

Why the difference? Are there factors that bias the numbers observed? It is believed that the discrepancy is caused by absorbing material in the interstellar medium that is concentrated in the plane of our Galaxy. The supernovae that have been observed are all quite close to us in the Galaxy; we suspect that ones further away, if they are near the plane of the Galaxy, are not seen because of obscuration by the interstellar medium. Correcting this bias as well as possible suggests that the real rate in our Galaxy is much the same as in other galaxies. There are approximately equal numbers of Type I and Type II supernovae.

8.3.5 Supernova 1987A

For almost 400 years no bright, nearby supernova had given astronomers the chance to check out their conjectures about the death of massive stars. During these centuries the available instrumentation grew: first the optical telescope was invented, then the other wavelengths of the electromagnetic spectrum were recognized and,

since the middle of the 20th century, telescopes have been developed to detect these too. Neutrino detectors, similar to those described in Section 2.2.6, were in place and waiting. What was really needed was a good supernova explosion to allow astrophysicists to check out their theories on how supernovae occurred, whether nucleosynthesis actually took place, and what happened to the core of the star.

Then on 24 February 1987 it happened. A Canadian astronomer, Ian Shelton, using a mountain-top telescope in Chile, found an unexpected bright star on a photographic plate he had just exposed, something that hadn't been there the previous night when he had also photographed that part of the sky. After 20 minutes trying to explain away the spot (OK, nobody's too bright in the cold at 3000 metres altitude at 3 o'clock in the morning) he looked outside and saw it was real. In a nearby galaxy in the southern sky, called the Large Magellanic Cloud (Figure 8.7), a star had exploded. Figure 8.8 shows this part of the sky before and after the explosion.

Figure 8.7 The Large Magellanic Cloud. This irregular galaxy is probably the nearest galactic neighbour to our own Galaxy. It is believed to be at a distance of about 52 kpc from the Sun. (D. Malin/AAO)

(a) (b)

Figure 8.8 Supernova 1987A. The left-hand image (a) shows a region of the Large Magellanic Cloud (Figure 8.7) which contains the supergiant star (indicated) that gave rise to Supernova 1987A. The panel on the right (b) shows the same region as it appeared after the eruption of the supernova. (D. Malin/AAO)

For every discovery there are, usually, several near misses. Some 19 hours earlier in Australia, Robert McNaught had photographed that part of the Large Magellanic Cloud at the Anglo-Australian Observatory. Although he developed the plate he did not examine it that night. Subsequently he found that he had the first photograph of the supernova – it was beginning to happen and at that stage was just becoming bright enough to be visible to the naked eye. Shelton is therefore credited with the discovery of **SN 1987A** (SN being the abbreviation for supernova, and 'A' indicating that it was the first one found in 1987.) However, McNaught's observation, combined with Shelton's negative observation the previous night, is scientifically important in pinning down the start of the event.

This supernova had already, unknowingly, been observed by neutrino detectors, and would be observed in all the major wavelength bands over the next few years. During the previous year, two underground neutrino detectors, not primarily designed for the detection of neutrinos from supernovae, had been sufficiently improved in sensitivity that they were able to play an important part in the study of this explosion. (Note that the Homestake mine experiment that was described in Chapter 2 was not sufficiently sensitive to detect neutrinos from SN 1987A, and that the Sudbury Neutrino Observatory, or SNO, had yet to be built in 1987.) One of the detectors was in a zinc mine in Kamioka in Japan (Figure 8.9), the other in a salt mine near Lake Erie in Ohio, USA. Simultaneously they detected a short burst of a few neutrinos lasting about 10 seconds, and well above the normal background rates. About 3 hours before McNaught's observation 12 neutrinos were counted in the Japanese detector and 8 in the American one. The number and energy of the particles in the neutrino burst fitted well with the prediction of what would be produced if the central core of a supergiant collapsed to nuclear densities. It appears that about 3×10^{46} J of energy were carried away by 4×10^{58} neutrinos. About 170 000 years after the explosion, as the burst of neutrinos swept though the Earth, 20 of them interacted in the two large underground detectors.

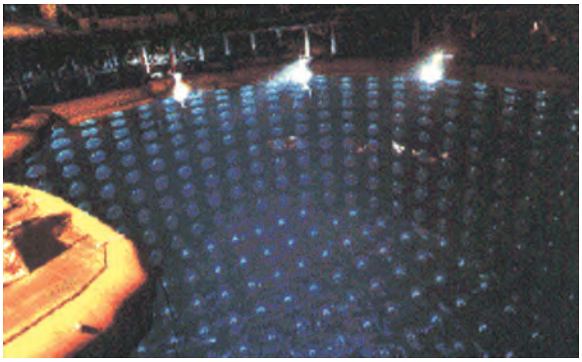


Figure 8.9 The Kamiokande II neutrino detector that detected 12 neutrinos from supernova 1987A. The heart of the experiment was this tank of ultra-pure water. Occasionally neutrinos would interact with electrons in the tank of water, resulting in a flash of light that could be detected by an array of photocells that are arranged around the tank. This experiment has now been superseded by a larger and more sensitive neutrino observatory called *Super-Kamiokande*.

About 1% of the energy of the collapsing star went into the shock wave, which slowly travelled out through the star and caused the increase in the luminosity. By that time the neutrinos had gone, at the speed of light, and so the neutrinos were detected a few hours before the star was seen to brighten.

QUESTION 8.3

Is it necessary for a cosmic source of neutrinos to be above the horizon for the detection of neutrinos here on Earth? Was this source above the horizon at the time of the detection?

It had been assumed that massive stars exploded as *red* supergiants, so it was something of a surprise when it became clear that the progenitor, the star that exploded producing SN 1987A, was the *blue* supergiant catalogued as Sanduleak –69°202, a $20M_{\odot}$ star of spectral class B. Ultraviolet observations made when the supernova had faded somewhat established that Sk –69°202 no longer existed, confirming the identification. This stimulated new work on the evolution of massive stars, and the circumstances that led up to the supernova are still a matter of research effort.

The spectrum of the supernova contains hydrogen lines, and it must therefore be classified as a Type II supernova, but SN 1987A was fainter, by a factor of ten, than the Type IIs that, up until then, were thought to be typical. This relatively low luminosity is thought to be connected to the unusual nature of the progenitor. The light curve in Figure 8.10 is a plot of the optical luminosity of the supernova against time. It strikingly confirms the theory that material is heated by γ-rays that are produced by the radioactive decay of ${}^{56}_{27}\mathrm{Co}$. From about 100 days to about 700 days after the outburst, the fading of the supernova follows the rate of radioactive decay of cobalt nuclei. Further evidence that the nuclear reactions are reasonably well understood came from infrared and γ-ray observations. Infrared spectrometers found spectral lines due to iron and cobalt, while γ-ray telescopes detected γ-rays with the energies expected from the decay of ${}^{56}_{27}\mathrm{Co}$. This was the first time that a direct check of the theory of element formation in supernovae had been possible.

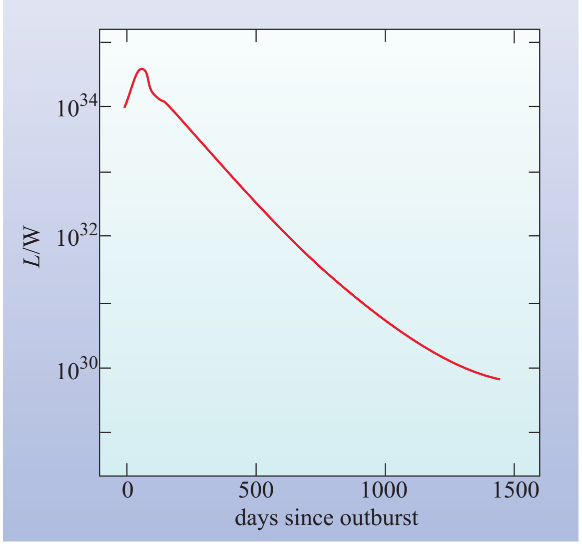


Figure 8.10 The light curve of SN 1987A.

QUESTION 8.4

If the decay of $^{56}_{27}Co$ is solely responsible for a supernova's luminosity, and each decay produces two γ-rays, one of energy 1.3×10^{-13} J and one of energy 1.9×10^{-13} J, what mass of cobalt nuclei must decay per second to produce a supernova luminosity of 10^{33} W?

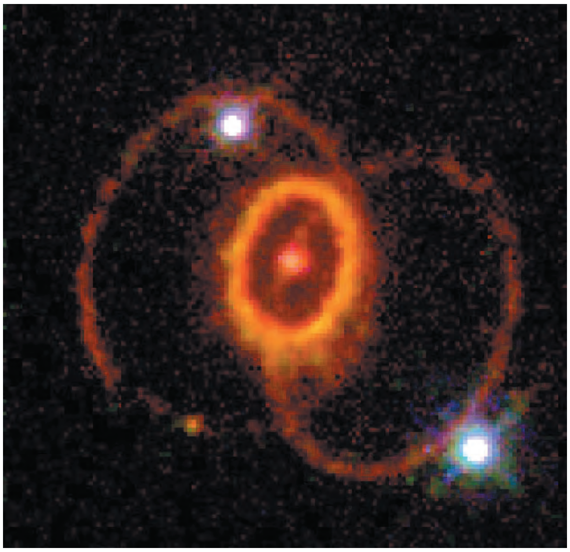
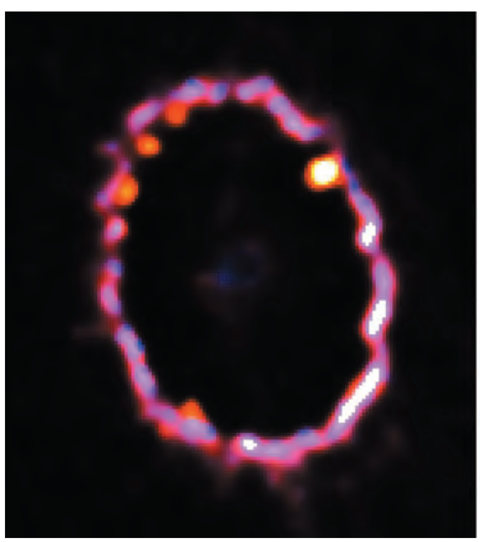


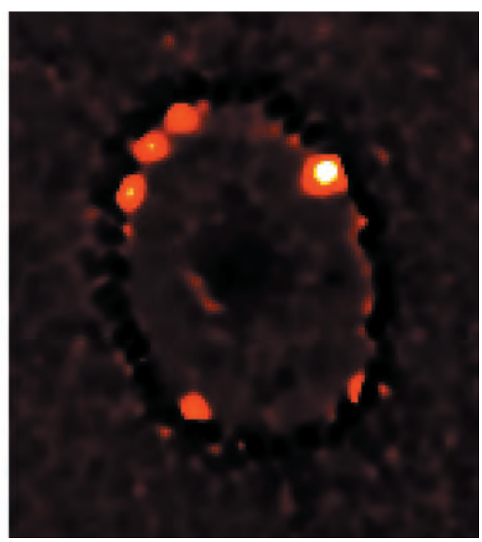
Figure 8.11 Rings of material around supernova 1987A that were ejected prior to the supernova explosion. The emission of light arises from the illumination of this material by electromagnetic radiation from the supernova, and was first seen in an observation made in February 1994 using the Hubble Space Telescope. The structure of these rings, which comprise an inner ring and two symmetrical outer rings, was an unexpected feature of SN 1987A. (STScI/NASA)

An intriguing aspect of supernova 1987A arises from the interaction between the supernova and shells of material that are believed to have been expelled by the pre-supernova star over the last 30 000 years or so. The first effect to be seen was the illumination of this material by the electromagnetic radiation from the supernova. The structure that was revealed comprised an inner ring and, surprisingly, two outer rings (Figure 8.11). This complex structure probably represents different episodes of mass loss from the pre-supernova star. The second interaction between the supernova and its environment arises from the impact of the expanding shock wave. The shock has now reached the material that appeared as the inner illuminated ring, and localized hot spots of shock-heated gas have been seen to emerge over the last few years. Figure 8.12 shows the appearance of the ring in February 2000 and the shock-heated features that appeared between 1997 and 2000.

How will SN 1987A appear thousands of years hence? Most probably it will develop a circular structure, such as that shown by the Cassiopeia A (Cas A) supernova remnant. The appearance of that supernova remnant at radio, X-ray and optical wavelengths is shown in Figure 8.13. Alternatively it could evolve into a rather irregular shape such as happened in the case of the Crab Nebula (Figure 8.14). In the Crab, the collapsed core has formed a rapidly rotating *neutron star* which is detectable from its pulsed emission of radio waves. Neutron stars that exhibit such pulses of electromagnetic radiation, typically at radio or X-ray wavelengths, are termed *pulsars*. The properties of pulsars will be explored in more detail in Chapter 9.

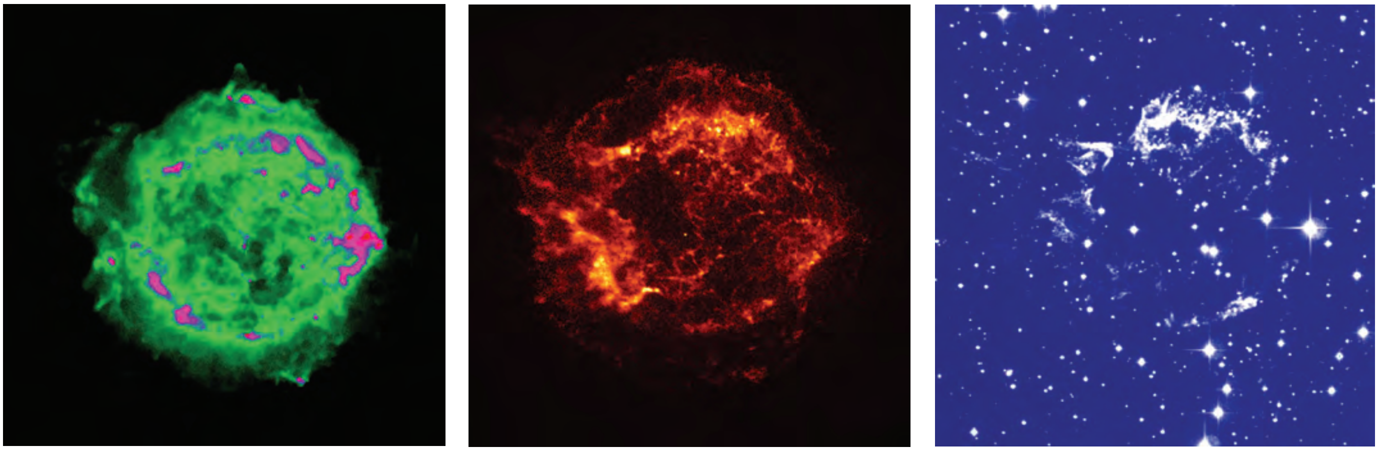


(a)



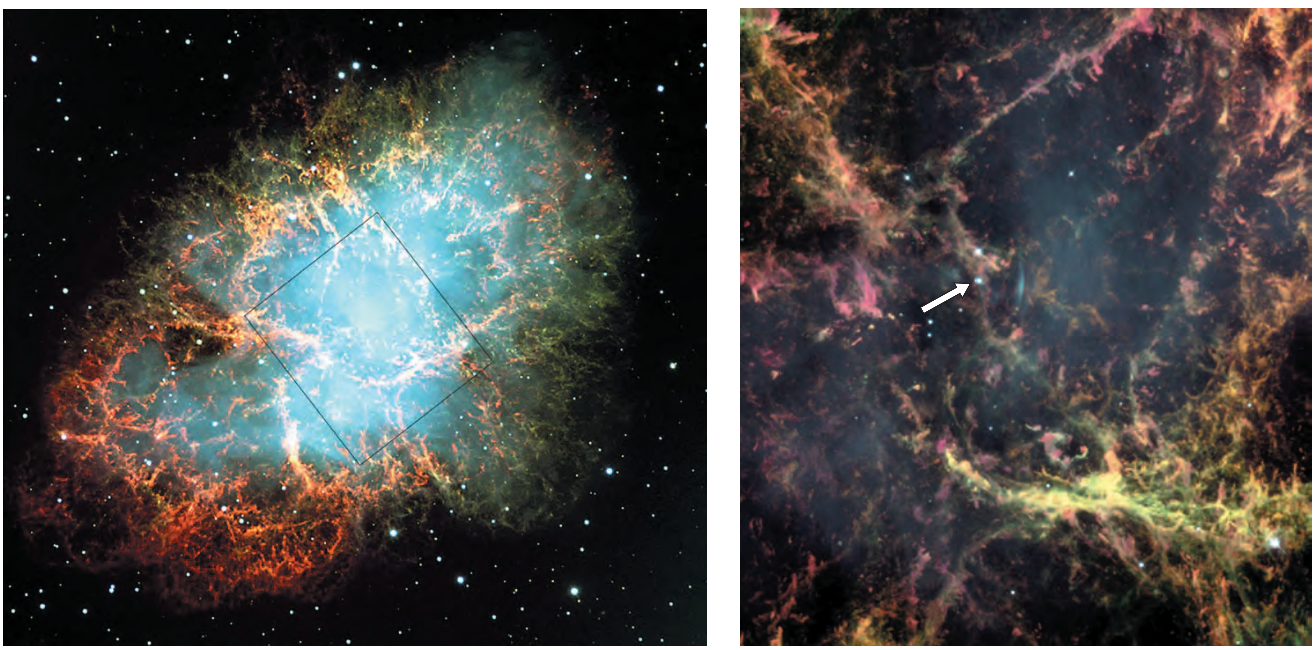
(b)

Figure 8.12 The inner ring of material around SN 1987A that was ejected prior to the supernova explosion is now being heated by the shock wave from the supernova. (a) shows the appearance of the inner ring in February 2000. (b) shows the features in the ring that had appeared between observations made in 1997 and in 2000, showing the emergence of several bright hot spots around the ring. These hot spots are attributed to the shock heating of clumps of material in the ring. (P. Challis, R. Kirshner, P. Garnavich/NASA)



(a) (b) (c)

Figure 8.13 The Cassiopeia A (Cas A) supernova remnant. The supernova is believed to have erupted about 300 years ago, although it is not recorded as having been seen at the time. These images show the remnant at (a) radio, (b) X-ray and (c) visible wavelengths. While the remnant is very clearly seen at radio and X-ray wavelengths, the optical image is somewhat less distinct. ((a) VLA; (b) NASA/CXC/SAO; (c) MDM Observatory)



(a) (b)

Figure 8.14 The Crab Nebula. The supernova that gave rise to the Crab Nebula was recorded by Chinese astronomers in AD1054. (a) This image at visible wavelengths was taken from a ground-based telescope and shows the supernova remnant as a rather irregular nebula that is now about 2 pc across. The square field shows the area that is shown in (b) observed using the Hubble Space Telescope. The pulsar, which is the remnant of the core of the star that gave rise to the supernova, is indicated. Note that both colour images were created by combining images taken though filters that are sensitive to particular spectral lines. ((a) ESO; (b) W. P. Blair (John Hopkins University))

8.4 Feeding the interstellar medium

In this section we look at how stars of any initial mass return material to the interstellar medium (ISM). Much of this material has been subject to nuclear processing in stars, and this has led over time to a change in the chemical composition of the ISM and of stars.

8.4.1 Dispersal of stellar material

■ Name three processes that you have already met that return stellar material to the interstellar medium.

❑ Stellar winds, the shedding of planetary nebulae, and supernovae.

These three mechanisms will be considered in turn, before we consider how the interstellar medium changes with time and the effect that this has on the compositions of stars.

Stellar winds and circumstellar shells

Stellar winds are a relatively gentle form of dispersal. All stars lose some matter in this way, but in our Galaxy the overall amount of matter returned by stellar winds to the ISM is dominated by the copious winds from hot (class O and B) stars, and by strong winds from cool red giants. These latter winds give rise to circumstellar shells similar to that shown in Figure 8.3. In their inner regions, circumstellar shells are kept moderately warm by the star's luminosity, with temperatures around 1000 K, not much less than that of the star's photosphere.

■ What is the range of photospheric temperatures of cool red giants?

❑ From Section 4.2.2, about 2000 to 3000 K.

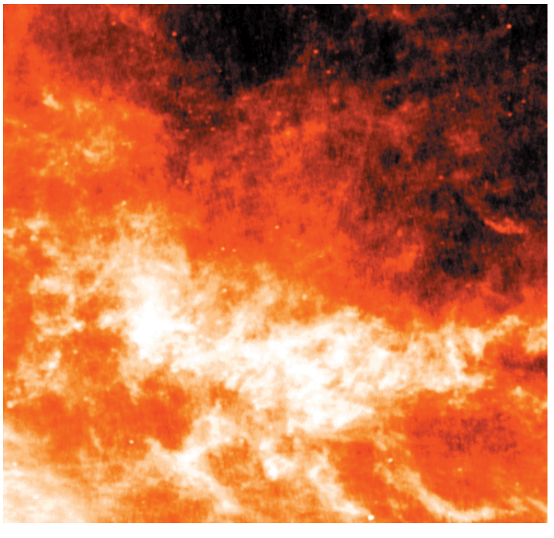


Figure 8.15 A region of interstellar cirrus as seen using IRAS. This image shows the emission from interstellar cirrus at a wavelength of 100 μm. The area of sky covered by this image is 12° square. (Data provided by IPAC, Caltech)

Circumstellar shells are, as you might expect, less dense than the photospheres of red giants, but are enormously dense by ISM standards, with $n \sim 10^{17}\,\mathrm{m}^{-3}$ in their inner regions. As has already been noted, these conditions result in the formation of dust grains and molecules. However, as the matter in such shells moves outwards it becomes less dense, and also cools, and the next we see of it might be the widespread but thin **interstellar cirrus**, so called because of its resemblance to the terrestrial cloud type called cirrus. An example of the interstellar variety is shown in Figure 8.15 – what we are seeing is thermal radiation from dust at about 20 K. Interstellar cirrus was discovered in 1983 from observations using the space-borne Infrared Astronomical Satellite (IRAS).

Ultimately, all matter from stellar winds becomes thinly dispersed.

Shedding of planetary nebulae

Slightly more violent than mass loss via stellar winds is the shedding of a planetary nebula. In Section 8.2 you saw that this is the fate of a giant, which becomes unstable and throws off a significant fraction of its mass. All but the lowest and highest mass stars become giants, and so planetary nebulae are an important source of matter for the ISM. The remnant star is very hot, and also emits a powerful wind. As a

result, planetary nebulae are hotter than circumstellar shells, with temperatures of order 10 000 K. They are also fairly dense, with $n \sim 10^9\ \text{m}^{-3}$. As in the case of stellar winds, the matter in planetary nebulae moves away from the star, at speeds of the order of several kilometres per second, cooling and thinning as it proceeds. It takes about 20 000 years for a planetary nebula to disperse – not long on the cosmic timescale.

Supernovae and their effects

Yet more violent ejection of stellar material occurs as a result of supernovae. We have already seen that Type II supernovae are cataclysmic stellar explosions, involving massive stars, in which most of a star's mass is flung into space. Supernovae of Type Ia, despite arising from a different explosion mechanism, also result in the dispersal of a large amount of stellar material. The explosive nature of supernovae might lead you to think that they are major sources of interstellar matter, but this is not really the case.

■ Why not?

❑ Supernovae are rare.

However, though supernovae are not major sources of *mass* for the ISM, they are important sources of heavy elements, a point to which we return later.

Supernovae also release huge amounts of *energy* into the ISM. In all supernovae it is believed that about 10^{44} J is carried off as kinetic energy in a radially expanding gas shell and about 10^{42} J in the form of electromagnetic radiation. The kinetic energy of the shell means that the expelled material does not simply cool and vanish into the general ISM in the manner of stellar winds and planetary nebulae, but wreaks far-ranging and profound changes. For example, the Vela supernova remnant (Figure 8.16), which is about 11 000 years old, has grown to a size of roughly 50 pc in diameter, and continues to violently disturb the interstellar medium that it impinges upon.

To explore the effects of Type II supernovae further, consider the speed at which the shell is initially expelled, given that

- of the ~5 to ~10 solar masses of material returned to the ISM, only about $0.25M_\odot$ carries most of this kinetic energy,
- the kinetic energy is almost entirely in the radial motion of the shell, rather than in the random thermal motions within it.

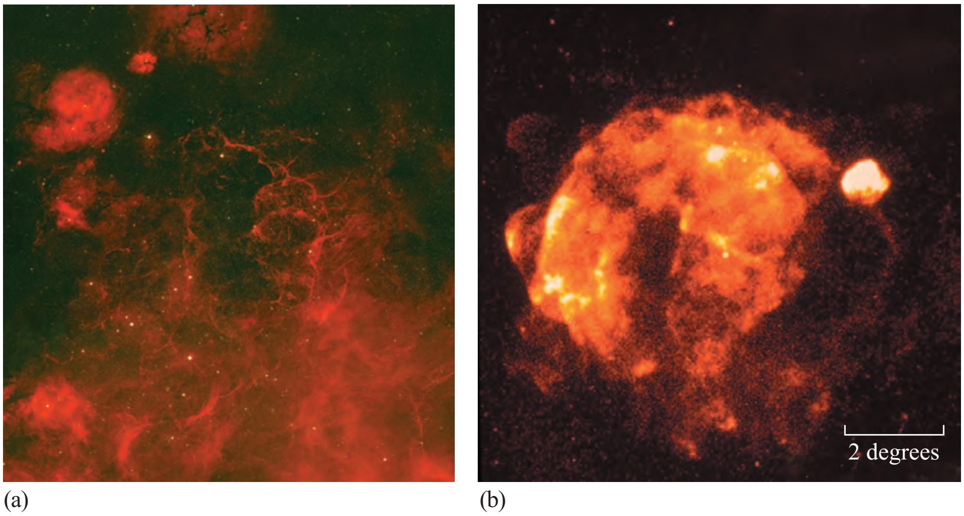


Figure 8.16 The Vela supernova remnant. This is the remnant of a supernova that occurred about 11 000 years ago. (a) An optical image that is sensitive to Hα emission. The remnant is visible as the filamentary structure in the central region of the field of view. Note that there are other Hα emitting regions also visible in this image which are not associated with the supernova remnant. (b) An X-ray image of the same field. The Vela supernova remnant is the large roughly circular feature that fills the field of view. The bright region at the upper right-hand edge of the remnant is the Puppis supernova remnant. This lies well beyond the Vela supernova remnant, and is not visible in the Hα image. The two supernova remnants are not physically associated with one another. ((a) Royal Observatory Edinburgh; (b) Max Planck Institute for Astrophysics)

QUESTION 8.5

Calculate the initial radial speed of such a shell.

Thus, a shell can have a radial speed that is a few per cent of the speed of light.

These high speeds mean that the kinetic energy of an atom in the shell is *far* higher than the thermal energy of a typical atom or molecule in the surrounding ISM. Because of this we get the following effects, which are summarized in Figure 8.17.

- The shell sweeps up much of the gas that it encounters, the swept-up gas being greatly compressed, greatly heated, and trapped within the shell, of which it becomes a part. The shell, which started hot and highly ionized, thus remains in this condition. It also remains thin compared with its radius.
- A small amount of gas finds its way into the volume of space enclosed by the shell. This gas has also been greatly heated, and expands to fill the volume, giving rise to a roughly spherical cavity pervaded by hot, low-density gas. The shell constitutes the supernova remnant. The temperatures within it range from 10^5 K to 10^7 K.
- The gas ahead of the shell gets no warning of the shell's approach, and thus its transition from a peaceful life to the tortured conditions in the shell is abrupt. Hence a shock front forms at the thin transition zone between these two regimes, and the swept-up gas is said to have suffered a **strong shock**.

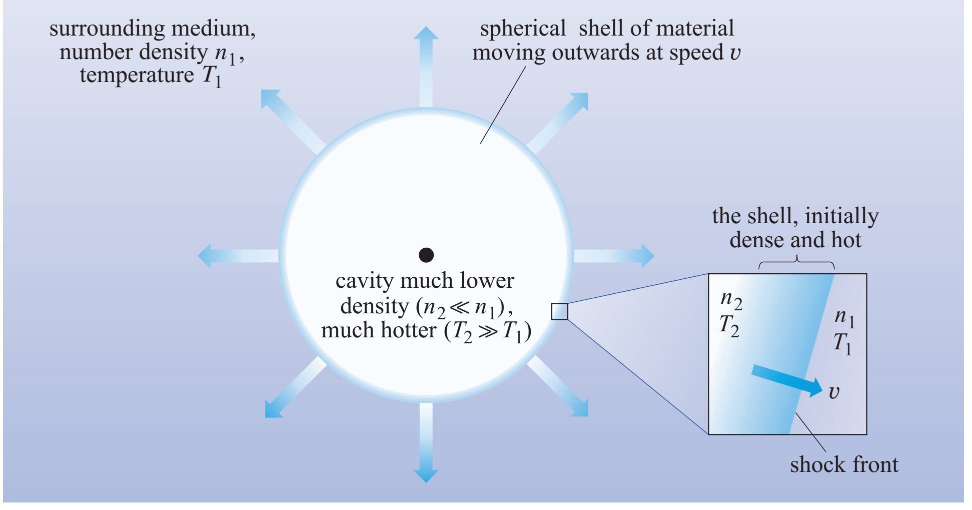


Figure 8.17 Conditions produced by the shell expelled by a supernova.

QUESTION 8.6

The interior of the supernova remnant is at a high temperature and so is a source of thermal radiation. However, the density of gas within the shell is very low, and so the spectrum of emission does not have a black-body spectrum. For a supernova remnant with a temperature of 10^6 K, estimate (a) the photon energy (in electronvolts), and (b) the wavelength at which you would expect the thermal emission from the supernova remnant to be strong. Which part of the spectrum does such emission correspond to?

The answer to Question 8.6 shows that the thermal emission from supernova remnants would be expected to give rise to X-rays. This is indeed the case as is illustrated in the X-ray images of the Cas A and Vela supernova remnants shown in Figures 8.13b and 8.16b, respectively.

Supernova remnants also emit copious amounts of radio waves. These radio waves originate from electrons that interact with the magnetic fields within the shell. Any charged particle that moves within a magnetic field is forced to move in a spiral around magnetic field lines (Figure 8.18). The spiralling motion of electrons in a magnetic field gives rise to the emission of electromagnetic radiation. If, as is the case in supernova remnants, the electrons are moving at speeds that are a substantial fraction of the speed of light, the emission is called **synchrotron radiation**. The spectrum of such emission is usually a rather featureless continuous spectrum. Such emission is common in very energetic environments that contain magnetic fields. An example of another astrophysical situation that you have already come across that generates synchrotron radiation is the radio emission that accompanies solar flares (Section 2.3.2).

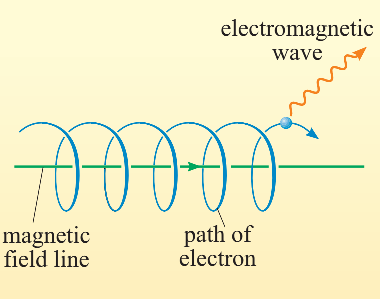


Figure 8.18 The spiralling motion of an electron in a magnetic field results in the emission of electromagnetic waves. (Note that the electron need not travel in the same direction as the field line – it could travel from right to left in this figure, but it would still spiral around the field line and still emit electromagnetic radiation.)

Supernova remnants are strong sources of synchrotron emission at radio wavelengths, as Figure 8.13a illustrates. Radio waves are not appreciably absorbed by the ISM, and so most remnants have been discovered through the radio waves they emit.

As the remnant expands its temperature falls and its X-ray emission also diminishes. However the synchrotron radio emission persists and is prominent for much of the 10^5 or so years before the shock front grinds to a halt, whereupon the supernova remnant dissolves into the general ISM.

Let's now briefly consider the growing cavity contained by the shell. The high temperatures (10^5 K to 10^6 K) ensure a high degree of ionization. Furthermore the density within the cavity is relatively low with number densities typically in the range $10^2\,m^{-3}$ to $10^4\,m^{-3}$. Under such conditions, the rate at which the gas can lose energy by emission of electromagnetic radiation is relatively low (for instance, it is far lower than the rate at which energy would be radiated by a black-body source of a similar size at the same temperature). Thus the material in the cavity remains very hot as the shell expands. The low radiative efficiency and the low densities result in such a slight amount of radiation from the cavity that there is little to see. A single cavity can grow to hundreds of parsecs across, and cavities can overlap and merge. Moreover, because the material in the cavity cannot cool very readily, it can outlast the supernova remnant. A consequence of this is that a large volume of the interstellar medium comprises hot, low-density material, not necessarily bounded by supernova remnants. This component of the ISM is the hot intercloud medium that was introduced in Section 5.2.1 and summarized in Table 5.1.

8.4.2 Evolution of the interstellar medium

Since stars return material that is, in many cases, enriched in heavy elements that are formed over the lifetimes of those stars, the ISM has evolved in its chemical composition. To summarize briefly the effects of stellar nucleosynthesis that have been discussed so far: stars with masses up to around $8M_\odot$ produce elements with atomic numbers up to about that of oxygen; stars with masses up to $11M_\odot$ produce elements up to and including magnesium, plus small amounts of the heavier elements; supernovae produce, during the explosion, a wide range of elements including those of the iron group and heavier elements.

Before considering what effect stellar nucleosynthesis might have had on the composition of material in our Galaxy, it is necessary to ask what the primordial composition of galactic material was. It is believed by the vast majority of astronomers that the origin of the Universe can best be described by a theory called the hot **big bang model**. It would be rather a lengthy diversion to explore this model in detail here, but a key feature is that early in the history of the Universe, all matter was in a very hot and dense plasma, and this plasma cooled with time. At a time when the Universe was about 1 second old, the temperature was about 10^{10} K and matter was in the form of protons, neutrons, and electrons. One of the theoretical predictions of the hot Big Bang model is that these conditions led to a process of **primordial nucleosynthesis** throughout the Universe that formed helium and tiny amounts of lithium but no heavier elements. The outcome of this is that the composition of matter just after the Big Bang would have been a mixture of hydrogen ($X \approx 0.78$) and helium ($Y \approx 0.22$) and extremely small quantities of lithium ($Z < 10^{-9}$). The uncertainty over the exact value of hydrogen mass fraction (X) and the helium mass fraction (Y) depends on the details of the model, but the limit that the metallicity (Z) is less than 10^{-9} is a firm prediction. It is a reasonable approximation to say that the primordial composition of matter was simply a mixture of hydrogen and helium.

■ What is the value of Z for a mixture that contains only hydrogen and helium?

❑ The definition of metallicity for a sample of material is

$$Z = \frac{\text{mass of heavy elements in sample}}{\text{mass of sample}}$$

Since the sample contains no heavy elements, $Z = 0$.

One way of characterizing the effect of stellar nucleosynthesis on the composition of the ISM and the stars that form from this material is to see how the metallicity has changed from its primordial value of $Z = 0$. The easiest place to measure this is in our local neighbourhood.

■ What is the metallicity of the material that the Sun formed from?

❑ In Section 2.2.3 it was stated that the value of Z throughout the Sun is about 2%, i.e. that $Z = 0.02$. Since the Sun has not (yet) synthesized any heavy elements, this must have been the metallicity of the material that the Sun formed from.

In fact, this value for the metallicity is typical for stars and the ISM in the part of the Galaxy where the Sun resides. A value of $Z = 0.02$ may not seem particularly large (although your perspective on this might change once you consider the prospects for your own existence in a Universe where $Z = 0$!), as it shows that only a small fraction of the mass that was originally in hydrogen and helium has been processed to heavy elements.

This might seem surprising in the light of the nuclear processing that has occurred in generations of stars, but is less so when one considers that much of the material returned to the ISM is from the envelopes of stars of low and medium mass, in which little enrichment of the heavy elements has occurred; most of the enriched material remains locked in the cores of these stars. Supernovae do lose more of their mass, and are massive to start with, but they are rare, and so return a relatively small amount of mass to the ISM.

The metallicity of material is only a crude measure of its composition; a fuller description is given by quoting the relative number of nuclei of different elements. This information on abundances of elements in interstellar material in our part of the Galaxy is shown in Figure 8.19. This graph shows the number of nuclei of different elements that would be present if we had a hypothetical sample of material from the interstellar medium that contained 10^6 nuclei of Si. This is essentially the same information as is given in Appendix A5, but displayed in this way it shows some interesting properties that reflect the processes of stellar nucleosynthesis. The most abundant elements are, of course, hydrogen and helium. There is a general trend that the abundance of elements seems to decrease with increasing mass number, which fits in well with some of the ideas of element formation that have been developed in the last two chapters:

- The end point of nuclear burning depends on stellar mass; the higher the stellar mass, the higher mass number of the main product of nuclear burning (up to a limit of $A \sim 56$).
- There are far more low-mass stars than high-mass stars, and this results in a greater enrichment in low mass-number elements than those of higher mass number.

There are clear discrepancies from this general trend and to some extent these can be attributed to the properties of the nuclei of individual elements. So, for instance, the high nuclear stability of the iron group elements is reflected by the high peak of the iron abundance.

While the general picture of the synthesis of elements is now well established, much research effort continues to be directed towards explaining the abundance distribution, as shown in Figure 8.19, in terms of the outcomes of particular stellar processes.

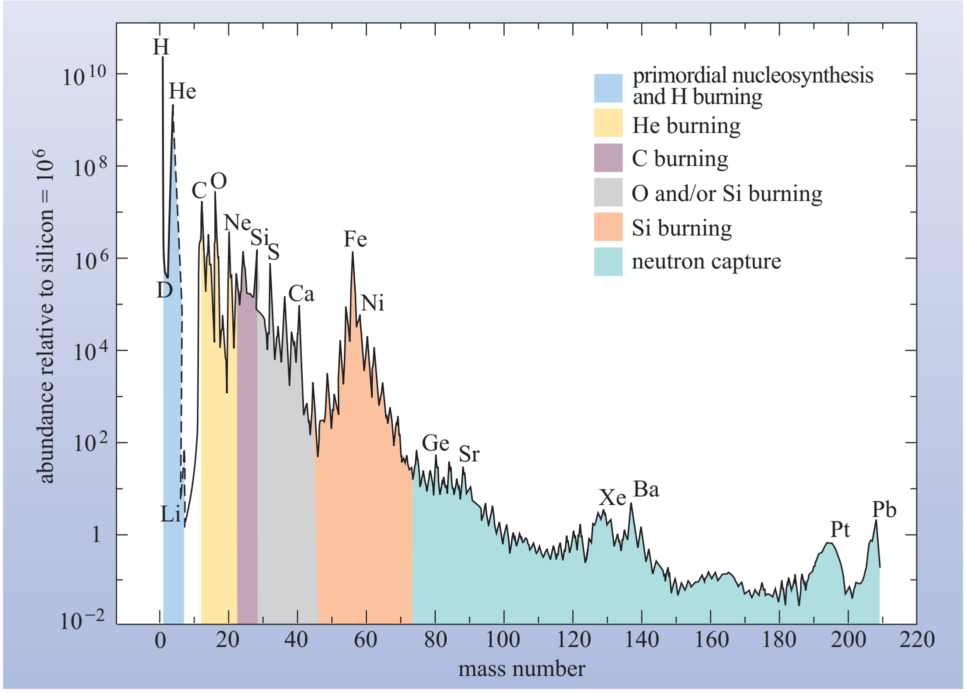


Figure 8.19 The distribution of elements by number in interstellar material in the region of the Galaxy that is local to the Sun. The stages of nuclear burning that give rise to elements at different mass numbers are indicated. (Adapted from Pagel, 1997)

8.4.3 Metallicities and stellar populations

The effect of stellar nucleosynthesis is to increase the metallicity of the ISM as time passes. The observed metallicity of a star provides an indication of the level of enrichment in heavy elements that had occurred in the ISM prior to the formation of that star.

■ Would you expect the original metallicity of a very old star to be higher or lower than that of the Sun?

❑ It is likely to be lower. The metallicity of the ISM by stellar nucleosynthesis increases with time. Hence an old star would have formed at a time when the metallicity of the ISM was lower than it was at the time that the Sun formed.

This general trend is indeed observed for stars in the Galaxy. Young stars tend to have high metallicities whereas older stars tend to have low metallicities. Astronomers categorize stars into classes called 'Populations' which correspond approximately with age. Roughly speaking, Population I stars are those that are young or of moderate age, and these stars are found to have metallicities of up to 2–3%. Population II stars appear to be intermediate age and old stars, and typically have metallicities of less than 0.8%.

The picture that emerges from the study of stellar populations is that there are some regions of the Galaxy, such as the halo (see the Introduction to the book), where star formation stopped a long time ago. The metallicity of stars (Population II) that we see in those regions corresponds to the level of enrichment of the ISM at that time. There are also other regions, such as the disc of the Galaxy, where star formation is recent or even on-going and the metallicity of stars in these regions (Population I) has been enhanced by the greater degree of cosmic recycling that has taken place.

■ Do the lowest metallicity stars correspond to material that formed from the primordial ISM?

❑ No, the lowest metallicity stars have a metallicity of about 0.1% of that of the Sun, hence $Z \sim 10^{-5}$ or so, whereas the primordial ISM would have had a metallicity of $Z < 10^{-9}$.

So even the oldest stars that have been observed in our Galaxy were formed from material that had already been enriched by a previous generation of stars. No stars have ever been observed that correspond to a primordial composition.

8.5 Summary of Chapter 8

Low-mass stars

- After core helium burning commences in a giant, its position on the H–R diagram will evolve towards a low temperature, high luminosity state called the asymptotic giant branch (AGB).
- AGB stars undergo a very high rate of mass loss. The exact reasons for this are unclear, but it is most likely linked either to large-scale global pulsations of the star (as exhibited by Mira variables) or to the onset of thermal pulses.
- After this stage, some stars eject a visible shell of material, of mass $0.1M_\odot$ to $0.2M_\odot$, called a planetary nebula.

High-mass stars

- On the last day of the life of a supergiant, the conditions in the core are such that nuclear fusion results in the formation of iron group elements.
- In the last few seconds of the life of a supergiant, the iron core collapses to nuclear densities with the copious emission of neutrinos.
- A shock wave is launched through the outer layers of the star; the effect of this, with assistance from the neutrinos, causes the outer layers to be explosively expelled. This is called a Type II (or possibly a Type Ib or Ic) supernova explosion.
- In the explosion, nuclear processes (fusion and the r-process) take place producing, in the main, iron group and heavier elements.
- Subsequent radioactive decay of some of these elements affects the post-explosion light curve of the supernova.

Supernova remnants

- Supernovae are a major source of energy for the interstellar medium. The kinetic energy of the shell of the supernova remnant causes a strong shock that heats material to a temperature of about 10^6 K.
- Supernova remnants grow to sizes of several hundred parsecs in extent. Merging of remnants occurs and forms an interconnected volume that is filled with hot gas from the supernova remnant cavities.

Cosmic recycling and enrichment in heavy elements

- Dispersal of stellar material may occur by stellar winds, planetary nebulae or by supernovae explosions.
- Stellar winds and planetary nebulae result in the return of a significant mass of material to the interstellar medium. This material is only modestly enriched in elements that are heavier than iron.
- Supernovae result in the return of a small mass of material to the interstellar medium, but are a major source of elements that are heavier than iron.
- As time has progressed, the metallicity of the interstellar medium has increased from the very low levels ($Z \sim 10^{-9}$) that resulted from primordial nucleosynthesis, to a value of about $Z \sim 3\%$ in star-forming regions at present.
- The stars in our Galaxy show different levels of enrichment in heavy elements that represent different epochs of star formation. Stars that have been formed recently tend to have higher metallicity than very old stars. However, no star has been observed that has a primordial composition.

Synchrotron radiation

- In the presence of a magnetic field, electrons will spiral around magnetic field lines. As they do so, they will emit electromagnetic radiation.
- If electrons are moving at speeds more than a few per cent of the speed of light, the radiation that is emitted is called synchrotron radiation. Synchrotron emission usually produces a featureless continuous spectrum.

Questions

QUESTION 8.7

A planetary nebula has a diameter of 0.4 pc and the speed of out-flowing material is $20\,\mathrm{km\,s^{-1}}$. Estimate the age of the planetary nebula and state any assumptions that you have to make in calculating your answer.

QUESTION 8.8

At its brightest, a hypothetical supernova has a luminosity of $5 \times 10^9 L_\odot$. It is sufficiently bright that it turns night into day – that is, it shines in the night sky as brightly as the Sun shines in the daytime sky, and delivers the same flux density to the Earth as does the Sun. How far away is it? Give your answer in astronomical units and parsecs. How many supergiant stars are there within that distance from the Earth?

QUESTION 8.9

Identify the following phases on the supernova light curve shown in Figure 8.6: (i) shock heating and expansion of the photosphere; (ii) temperature dropping but surface expanding; (iii) temperature and radius of visible surface approximately constant; (iv) visible surface shrinking at constant temperature; (v) γ-ray heating.

QUESTION 8.10

Use the data in Table 8.2 to decide whether the following isotopes of palladium (Pd) could be formed by the s-process starting from a sample of pure ${}^{104}_{46}\mathrm{Pd}$: (a) ${}^{108}_{46}\mathrm{Pd}$ and (b) ${}^{110}_{46}\mathrm{Pd}$.

Table 8.2 Stability data for some isotopes of palladium (Pd, $Z = 46$). (Note that there are more isotopes of palladium than are shown here.)

	Mass number A						
	104	105	106	107	108	109	110
type of radioactive decay	none	none	none	β^--decay	none	β^--decay	none
product of radioactive decay	–	–	–	${}^{107}_{47}\mathrm{Ag}$	–	${}^{109}_{47}\mathrm{Ag}$	–
half-life	stable	stable	stable	6.5×10^6 years	stable	13.7 hours	stable

QUESTION 8.11

If there were no supernova explosions, and massive stars quietly collapsed in on their iron cores, how would the chemical composition of the interstellar medium be different?